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Chapter
3.2.3 (e) Tropical Islands

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3.2.3 (e) TROPICAL ISLANDS

3.2.3.1 Introduction

The fate of any trace substance when released into an ecosystem is determined by many indigenous factors such as the geochemical characteristics of the parent materials, the unique properties of the soil system, and the regional climate. The biota of the ecosystem interact with trace substances in a direct way by taking up the trace materials into plants, either by aerosol deposition onto leaf surfaces, or through the root system from the soil solution. Plants are consumed by resident animal populations or man, and the trace substance enters food chains, in some cases within days after introduction. Plant residues in the soil in the form of undecomposed organic matter (humus) or organic acids in the soil matrix may exhibit strong complexation effects for both organic and inorganic substances. We have studied some of these basic interrelationships at the atolls in the Marshall Islands where radionuclides were released into the atoll environment during the atmospheric nuclear weapons testing program from 1946 to 1958.

3.2.3.2 Atoll Environment

The island environments of the atolls in the Marshall Islands represent a unique ecosystem where radionuclides that were introduced between 1946–1958 have had nearly 40 y to equilibrate. Bikini and Enewetak Atolls were the sites of 66 atmospheric nuclear weapons tests. These atolls are composed of coral limestone, which has accumulated on old igneous seamounts that arise in the Pacific Basin. The depth of coralline deposits beneath these atolls is about 4,000 feet at which point there is contact with primordial igneous rocks. An atoll is usually composed of a discontinuous series of islands on a ring of coral reef that surrounds a relatively shallow lagoon. An actively growing reef of coral organisms is present on the seaward side of the atoll, and coral beaches occur on the lagoon side.

The biota of the atolls is quite restricted because of the remoteness from continental masses that typically supply organisms for island colonization. Most of the vegetation on the atolls has arrived there by either water or animal transport. Most of the plant species that comprise the stable, climax vegetation of the atolls in the Marshall Islands are pantropical in distribution. The coconut palm, *Cocos nucifera,* and the pisonia tree, *Pisonia grandis,* are good examples of the pantropical floristic element, and these species occur throughout the Pacific Basin on islands and atolls.

Disturbed areas that were created in the 1950's have not returned to the stable tropical forest type and are present as open woodlands of *Messerschmidia argentea* and *Scaevola frutescens,* with vines, sedges, and grasses occurring between the clumps of low trees and shrubs.

The amount and frequency of rainfall at the atolls are of paramount importance in the cycling of a mobile ion such as cesium-137 (^{137}Cs). Most of the annual rainfall occurs from May through November; the months from December through April tend to be very dry. About 50% of the annual rainfall occurs from August through

November. Rainfall is variable and generally between 114 and 140 cm of rain per year in the northern Marshall Islands to as much as 380 cm per year in the southern Marshall Islands. The lack of rainfall during some years seriously affects the growth of vegetation, and in drought years some species die back. The northern Marshall Islands, where most of the research has occurred, are in the drier part of the Pacific region, and native agriculture attempted in this area often does not succeed with rainfall as the only source of water.

3.2.3.3 Radionuclide Distribution in the Soil

The unique properties of the soil at the atolls dictate to a large extent the distribution and cycling of radionuclides in the ecosystem. The composition of coral soil at Bikini Atoll is listed in Table 3.2.3.1. The soil is composed primarily of calcium carbonate ($CaCO_3$) with some magnesium carbonate ($MgCO_3$) and no silica-clay component. The pH is high, ranging from 7.7 to 9.0. The surface horizons are high in organic content (as much as 14%), although the organic content of the soil drops markedly with depth in the soil column. The soil is low in exchangeable potassium (K) (<50 ppm) and marginal in phosphorus (P) and trace-mineral content. Some of the native plant species and most introduced species show definite signs of K deficiency. In fact, with most introduced food crops and ornamental plants, growth is very limited without addition of K as well as nitrogen (N), P, and trace minerals.

The distribution of the radionuclides with depth in the soil column is essentially exponential, with the highest concentrations in the top few centimeters of the soil column (Figure 3.2.3.1). The concentration of ^{137}Cs and strontium-90 (^{90}Sr) are generally very similar at the atolls. However, ^{137}Cs is the most significant radionuclide contributing to the dose to people inhabiting the atolls, as will be discussed later. The concentration of plutonium-239+240 ($^{239+240}Pu$) and americium-241 (^{241}Am) are much less than that of ^{137}Cs and ^{90}Sr. Other radionuclides present a few years ago, such as cobalt-60 (^{60}Co), have essentially disappeared due to radiological decay. Most of the activity is within the top 25–40 cm of the soil column, which is where most of the organic material is located that has accumulated over the centuries on the islands. Below the organic layer, the activity concentration drops rapidly and is generally very low. The small amount of radionuclide activity present all the way to the groundwater represents the fraction of the soil inventory of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$, and ^{241}Am that is solubilized and carried to the groundwater when rainfall is adequate to cause through-flow of rain water and recharge of the underground lens system.

3.2.3.4 Radionuclide Uptake and Cycling

3.2.3.4.1 Cesium-137 and Strontium-90

The fundamental composition of the soil ($CaCO_3$, organic component, and no clay) produces dramatic differences in the uptake of ^{137}Cs and ^{90}Sr at the Marshall Islands compared to the uptake rates in the published literature, which are based primarily on silica-clay type soils. For example, the concentration ratio (CR), defined as the activity concentration of the radionuclide per gram of wet plant weight divided by the activity concentration per gram of dry soil, is about 0.1 for ^{137}Cs and about 1.0 for ^{90}Sr in silicate soils (Ng et al., 1982). However, in the coral soils in the

Table 3.2.3.1. Composition of coral soil from Bikini and Eneu Islands.

Island location and depth cm	ph[b]	Total[a] Sr (%)	Ca (%)	Mg (%)	P[c] (%)	N (%)	Organic matter[d] (%)	Extractable K[e] (ppm)
Bikini No. 1								
0–5	7.7	0.38	30.4	.95	1.35	0.64	14.4	79
5–10	7.8	0.39	30.8	.89	1.28	0.62	13.2	26
10–15	7.9	0.39	30.9	.89	1.29	0.63	12.3	20
15–25	7.9	0.40	31.9	.86	1.17	0.50	10.6	23
25–40	8.3	0.39	34.3	1.28	0.67	0.19	4.5	4
20–60	8.4	0.31	34.5	2.05	0.16	0.11	1.6	3
Bikini No. 2								
0–5	7.8	0.40	31.0	1.02	0.82	0.49	10.7	50
5–10	8.0	0.40	32.4	1.09	0.71	0.46	8.5	24
10–15	7.9	0.38	33.1	1.18	0.56	0.35	7.4	24
15–40	8.2	0.38	34.7	1.79	0.32	0.11	1.6	6
Eneu No. 1								
0–5	7.7	0.32	32.0	1.74	0.085	0.30	5.1	41
5–10	8.0	0.34	32.6	1.76	0.055	0.35	5.6	20
10–15	8.0	0.31	34.3	2.08	0.037	0.17	2.6	9
15–25	8.4	0.28	34.0	2.40	0.016	0.06	0.9	1
25–40	8.7	0.28	34.4	2.48	0.014	0.05	0.8	1
40–60	8.9	0.30	33.3	2.37	0.015	0.03	0.6	<1

a Stable cesium was below detection limit (1.3 ppm).
b pH in water.
c High phosphorus values indicate ancient guano deposition.
d Organic matter by wet oxidation.
e Extractable in N NH_4 acetate.

Marshall Islands the CR for ^{137}Cs is about 5 while that for ^{90}Sr is about 0.001 (Robison et al., 1988; Koranda et al., 1978). It is generally high for ^{137}Cs and low for ^{90}Sr in all the plant species that have been analyzed (Table 3.2.3.2). The ^{90}Sr replaces Ca in the $CaCO_3$ matrix of the coral soil, and is relatively unavailable for uptake; the ^{137}Cs is bound to the organic fraction of the coral soil and is relatively more available than in silica-clay soils where the ^{137}Cs is bound by mineral clays.

If published literature values for the CR had been used along with the concentration of ^{137}Cs and ^{90}Sr in soil to predict radionuclide concentrations in foods at the atolls, a grievous error would have resulted and the estimated doses would have been very wrong. Consequently, the fundamental composition of the soil has a great influence on the uptake and cycling of radionuclides.

It has been demonstrated in many biological systems that K is preferred over Cs and that plants will selectively take up K and discriminate against Cs (Handley and Oversheet, 1961; Middleton et al., 1960; Nishita et al., 1962; Wallace et al., 1983). However, when the concentration of K is below or near the margin of that required for optimum function, as it is at the atolls, then Cs can act as a substitute, to limited degree, for K and is taken up and incorporated in the plant.

Early studies and measurements were concerned with the distribution of radionuclides in the atoll ecosystem. Because of the importance of ^{137}Cs in the atoll environment, a landscape inventory was made at Enewetak Atoll on Engebi island to determine the distribution of ^{137}Cs in the soil and above-ground biomass. The data indicated that approximately 3 to 5% of the ^{137}Cs inventory in the soil was present in the vegetation at any time. This suggested that the soil-complexed pool of ^{137}Cs was tightly held and not available to the plant.

A laboratory study concerned with the availability of soil-complexed ^{137}Cs was made to verify the low apparent availability in the ecological inventory. Five columns each with approximately 3 kg of soil were setup and leached with distilled water. The pore water was allowed to remain in the soil for varying lengths of time and then leached with 10 times the pore volume. The data from this experiment are shown in Table 3.2.3.3. The availability of the soil-complexed ^{137}Cs was observed to be between 3 and 4% in this laboratory experiment, which was in agreement with the ecological measurements made previously.

A third and broader field experiment was then initiated and involved a hectare of atoll surface. The surface of the ground was irrigated with overhead sprinklers using seawater, and the presence of ^{137}Cs was monitored in the groundwater lens beneath the soil. After delivering 20 meters of rainfall to the plot, it was apparent that a pulse of ^{137}Cs had been leached to the groundwater lens, and thereafter no ^{137}Cs appeared in the groundwater compartment. The amount of ^{137}Cs appearing in the groundwater lens was on the order of 3 to 5% of the soil-complexed inventory.

These three experiments indicated that ^{137}Cs was tightly held in the organic stratum of coral soil on the atolls, and, in general, did not respond to the leaching effect of rainfall. The small fraction of ^{137}Cs circulating in the biomass pool was found to be transferred to man via terrestrial foods.

Table 3.2.3.2. The concentration ratio (CR) for ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am at Bikini Island for several species of vegetation.

	Mean (median) CR (Bq/g in fruit, wet weight / Bq/g in 0–40 cm soil, dry weight)			
	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Drinking coconut meat	5.5(3.4)	6.1E-3(4.5E-3)	2.8E-5(7.1E-6)	5.3E-5(1.4E-5)
Drinking coconut fluid	2.1(1.3)	—	—	—
Copra meat	10(4.2)	4.6E-3(3.1E-3)	1.9E-5(6.0E-6)	3.1E-5(8.2E-6)
Breadfruit	0.8(0.6)	0.057(0.055)	1.3E-5(4.2E-6)	2.4E-5(6.5E-6)
Pandanus	15(11)	0.12(0.041)	2.3E-5(1.3E-5)	6.3E-5(3.0E-5)

Table 3.2.3.3. The release of ^{137}Cs from Enewetak Atoll soil by leaching in laboraory columns.

Column	A	B	C	D	E
Weight (g)	3105	3270	3000	3000	3000
^{137}Cs Bq/g	1.24	1.20	1.27	1.18	1.19
Total Bq in column	3852	3912	3800	3544	3556
Bq leached after 2 days[α]	41	40.5	41.2	39.7	50.6
Bq leached after 48 days					
A[b]	10.8	9.93	8.63	10.7	9.19
B	22.2	24.5	14.8	21.7	20.2
C	7.07	3.07	3.59	15.9	5.48
D	2.78	2.22	6.96	0.78	0.78
Total	42.8	39.7	34.0	49.1	35.7
Bq leached after 15 days	3.19	3.44	3.19	1.52	2.89
Bq leached after 15 days	1.33	1.30	1.37	1.04	1.11
Bq leached after 60 days					
A	9.22	10.6	10.2	8.93	7.85
B	28.5	41.2	30.7	23.4	25.3
Total	37.7	51.7	40.8	32.3	33.1
Total Bq leached	126	137	121	124	123
%Total column activity leached	3.3	3.5	3.2	3.5	3.5

α Period of exchange of soil with pore water; water was removed after exchange period.

b Successive leaching with 10X pore volume in each sub-period.

3.2.3.4.2 Plutonium and Americum

The atoll ecosystem is an excellent place in which to evaluate the root uptake of the transuranic radionuclides $^{239+240}Pu$ and ^{241}Am. Determining what fractions of the total Pu and Am observed in plants is due to root uptake versus deposition on the plants via soil resuspension has been a difficult problem in most environments with the types of food crops generally used. However, in the atoll system most all of the food crops (coconut, breadfruit, pandanus, etc.) grow to such heights that the fruit and canopy are well above resuspended soil aerosol and deposition is essentially not a problem. In addition, the edible fruits have dense, thick layers that protect the edible portion of the fruit; these protective layers must be husked, peeled or removed in some manner in order to eat the fruit. Consequently, the edible portion is in a sense "sealed" from any deposition type of contamination. The Pu and Am observed in foods can only be derived via root uptake.

The CR for Pu and Am is about 10^{-6} to 10^{-5} at Bikini Island. This is in agreement with some greenhouse, pot culture studies where experimental design eliminated any resuspension. The general magnitude of uptake of Pu and Am seems to be about the same over a wide range of soil types, with the coral soils being at one extreme with high pH and nearly pure $CaCO_3$ plus organic material. This is in stark contrast to the very different CR's observed for ^{137}Cs and ^{90}Sr in different soil systems.

3.2.3.5 Radiological Dose Estimates

The potential exposure pathways that had to be evaluated at islands in the atolls are terrestrial foods, external gamma, inhalation (resuspension), marine foods, catchment water (rainwater), and groundwater. The relative importance of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$,and ^{241}Am, the only radionuclides of any significance still remaining on the islands, for each of the exposure pathways can be seen in Table 3.2.3.4. The ingestion pathway accounts for about 85% of the effective 30- and 50-y integral dose equivalent and ^{137}Cs contributes almost all of that. The external gamma pathway accounts for about 14% of the dose equivalent and is due almost entirely to ^{137}Cs. The most significant pathway for $^{239+240}Pu$ and ^{241}Am is inhalation, but overall, the transuranic radionuclides and ^{90}Sr contribute a small fraction of the total estimated dose. The significance of the terrestrial food chain in the ingestion pathway is shown in Table 3.2.3.5; it accounts for more than 95% of the dose via ingestion. The marine foods, water, and inhalation pathways contribute a very small portion of the total dose equivalent. This result is interesting because much of the activity from the nuclear tests that remained on the atoll was injected into the marine environment. However, some 30 to 40 years after the end of the tests the major pathway for dose to people inhabiting the atolls is from the uptake of ^{137}Cs into terrestrial foods (Robison, 1983; Robison et al., 1987; Robison and Phillips, 1989).

3.2.3.6 Remedial Measures for ^{137}Cs Uptake

The $CaCO_3$ nature of the soil and the low exchangeable K characteristics (see Table 3.2.3.1) of coral islands provide the conditions for the high uptake of ^{137}Cs that are observed. On the other hand, these conditions would seem to provide a situation in which K added to the system might alter the uptake of ^{137}Cs.

Table 3.2.3.4. The 30–, 50–, and 70–y integral dose equivalents in Sv for whole body (WB), bone marrow (BM), and bone surface (BS) at Enjebi Island assuming imported foods are available.

Pathway and radionuclide	30 y[a]			50 y[a]			70 y[a]		
	WB	BM	BS	WB	BM	BS	WB	BM	BS
External gamma	0.005	0.005	0.005	0.0068	0.0068	0.0068	0.0079	0.0079	0.0079
Ingestion									
^{137}CS	0.030	0.030	0.030	0.044	0.044	0.044	0.054	0.054	0.054
^{90}Sr	—	0.0012	0.0027	—	0.0018	0.0040	—	0.0022	0.0048
$^{239+240}Pu$	—	0.000017	0.00022	—	0.000045	0.00059	—	0.000082	0.0011
^{241}Am	—	0.000014	0.00018	—	0.000038	0.0005	—	0.000071	0.0009
Inhalation									
$^{239+240}Pu$	—	0.00053	0.0060	—	0.0013	0.015	—	0.0024	0.028
^{214}Am	—	0.00022	0.0026	—	0.00057	0.0066	—	0.0010	0.012
Total	0.035	0.037	0.047	0.051	0.055	0.077	0.062	0.068	0.11

[a] The effective integral dose equivalents for 30-, 50-, and 70-y are 0.036 Sv, 0.053 Sv, and 0.066 Sv, respectively.

Consequently, experimental plantings of coconut palms, pandanus, breadfruit, and other food plants have been established at Enewetak and Bikini Atolls to study radionuclide uptake under semi-controlled conditions to provide guidance on the resettlement of the atolls by the native population.

Several experiments using large areas of the coconut grove on Bikini Island have been implemented. The experiments include surface application of K ranging from 666 kg/ha to 5550 kg/ha, in the form of N,P,K fertilizer org14

KCl and the number of trees per experiment ranging from 10 to 120. The total K has been applied over a 3-year period on some experiments and in one application for other experiments. Similar experiments have also been conducted on breadfruit and pandanus trees.

The results of all the experiments show a decrease in the uptake of ^{137}Cs to about 5% of the pre-treatment concentration of ^{137}Cs in the fruits. The initial results from a recent experiment using 666 kg/ha indicate a reduced uptake of ^{137}Cs similar to that observed for the higher rates of added K. Examples of the results are shown for two of the experiments in Figure 3.2.3.2 and 3.2.3.3. These results are extremely important to resettlement options at the atolls, because the great reduction of ^{137}Cs in the food crops leads to estimated doses at the islands that are below 1.7 mSv/y. Consequently, the total annual dose equivalent (background plus man made) at the islands is equal to or less than one half the annual background does equivalent in the United States, Europe, and Asia. In addition to blocking the uptake of ^{137}Cs, the treatment with KCl (or N,P,K) increases the growth rate and productivity of the plants as has been observed in other tropical locations (Vernon et al., 1976). The ^{137}Cs, although blocked from uptake by plants, is still present on the island.

The alternative remedial measure for rehabilitation of the islands is to excavate and dispose of the surface soil (top 40 cm) to get rid of the radionuclides, particularly ^{137}Cs. Although this method is very effective in eliminating the radionuclides from the islands, it has significant environmental consequences. All of the standing vegetation, which includes mature coconut groves that have taken 20 y to develop, breadfruit, and pandanus trees, must be removed. Then the top 40 cm of the soil column can be removed. The top 40 cm contains most of the radionuclides, but also contains all the organic material that has taken centuries to develop on the coral islands; below the organic-material-containing layer is essentially beach sand. This soil-organic layer provides nearly all the nutrients needed for plant growth and contributes a significant fraction of the water-retention capacity of the coral soil. The consequences of excavation of the top 40 cm will have long-term ecological and agricultural effects; a very long-term commitment, probably the order of decades, will be required to rebuild the soil and revegetate the islands.

3.2.3.7 Conclusion

Radioecological studies on atolls in the Marshall Islands have shown that the unique and endemic characteristics of the substratum, climate, and biota produce differences in radionuclide behavior from that observed in other biomes. A reversal of temperate region soil to plant concentration ratios (CR) for ^{137}Cs and ^{90}Sr occurs on the atolls, with higher concentration effects being seen for ^{137}Cs. The mean (CR) for ^{137}Cs in atoll plants is about 5.0, and ^{90}Sr ratios range from 0.005 to 0.05. In silicate soils, the ^{137}Cs CR is 0.1 and 1.0 for ^{90}Sr. Apparently strontium enters the calcium carbonate matrix of the atoll soil and is tightly held there. Also, the pool of stable Sr is much greater than the pool of stable Cs in the atoll soil. The organic acid stratum of the atoll soil retains ^{137}Cs that is available to plants.

Radionuclides are concentrated in the surface 40 cm of the white coral soil, which is typically stained brown from organic acids leached from plant residues. The retention of ^{137}Cs in the stratum of the soil where organic material accumulates produces a small, cycling, and biologically available pool of the radionuclide. Laboratory and large field experiments have shown that less than 5% of the soil-bound and landscape inventory of ^{137}Cs is cycling and available to plants. The available pool of ^{137}Cs enters food plants solely by root uptake and is responsible for elevated body burdens in the native population when those foods are consumed for long periods. Leaves and fruit of plants have the highest concentration of ^{137}Cs; however, the concentration in roots is approximately the same as the surrounding soil.

Large-scale field experiments have been conducted at the atolls on coconut trees and other food plants to determine the effects of added K on the uptake of ^{137}Cs. Potassium supplements applied to coconut trees reduced ^{137}Cs uptake to about 5% of the pretreatment concentration. Similar results have been observed in about 20 different plant species. Nitrogen and phosphorus supplements did not produce as significant a decrease in ^{137}Cs uptake, but all nutrients increased yields and vegetative growth. The reduction of ^{137}Cs uptake by potassium supplementation is sufficient to reduce the annual radiation dose equivalent to a resident native population consuming atoll vegetation to a level below the annual natural background dose equivalent received by a typical Northern Hemisphere inhabitant.

3.2.3.8 References

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Figure 3.2.3.1 The median concentration of ^{137}Cs, ^{90}Sr, $^{239+240}Pu$ and ^{241}Am as a function of depth in the soil column on Bikini Island.

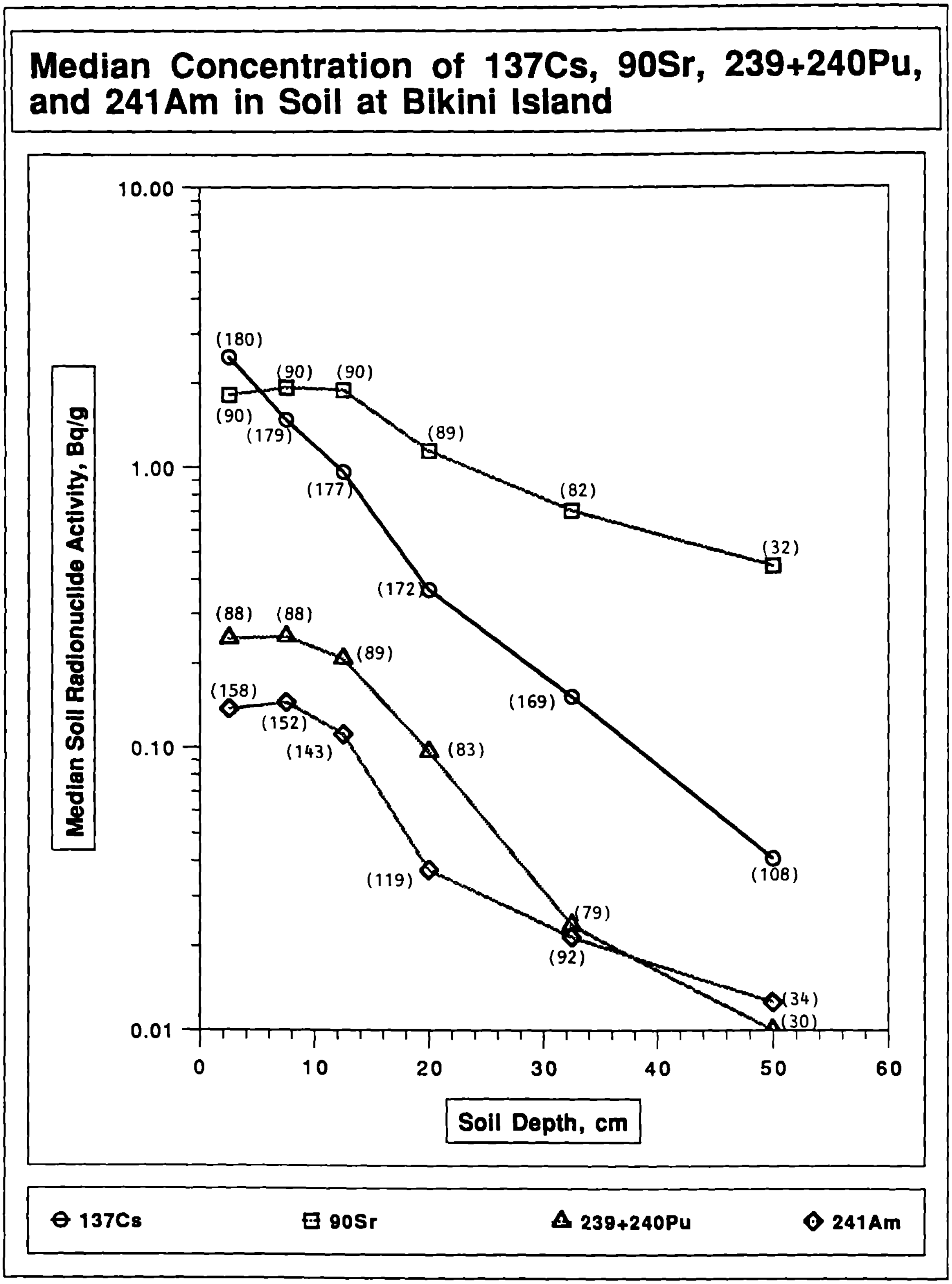

Median Concentration of 137Cs, 90Sr, 239+240Pu, and 241Am in Soil at Bikini Island
Median Soil Radionuclide Activity, Bq/g
10.00
1.00
0.10
0.01
0
10
20
30
40
50
60
Soil Depth, cm
(180)
(179)
(177)
(172)
(169)
(108)
(90)
(90)
(90)
(89)
(82)
(32)
(88)
(88)
(89)
(83)
(79)
(30)
(158)
(152)
(143)
(119)
(92)
(34)
137Cs
90Sr
239+240Pu
241Am

Figure 3.2.3.2 The effect of 1110 and 2220 kg K/ha, 500 kg NP/ha, 1110 kg K/ha + 500 kg NP/ha and 2220 kg K/ha + 500 kg NP/ha on the uptake of ^{137}Cs in drinking coconuts at Bikini Island.

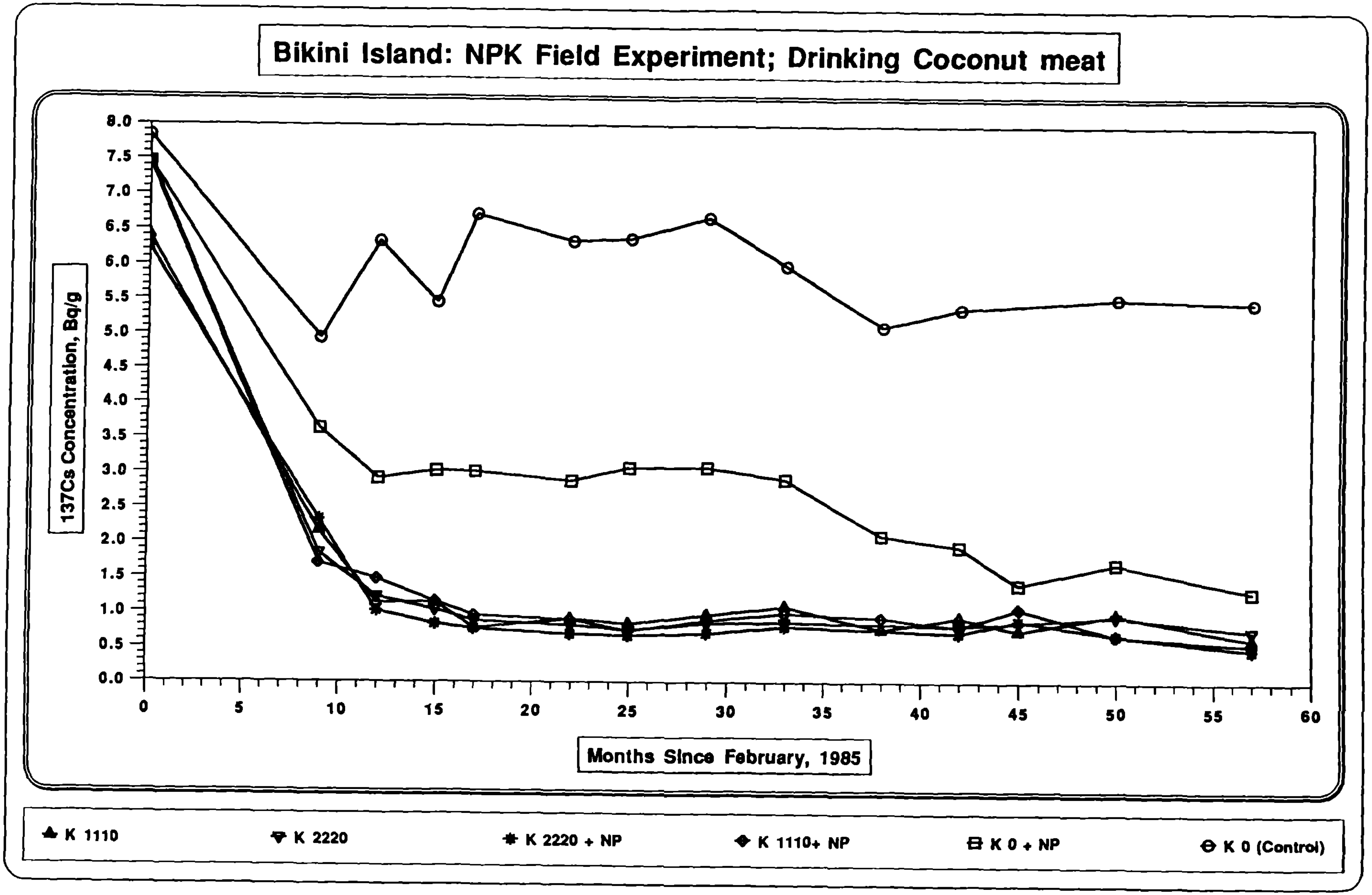
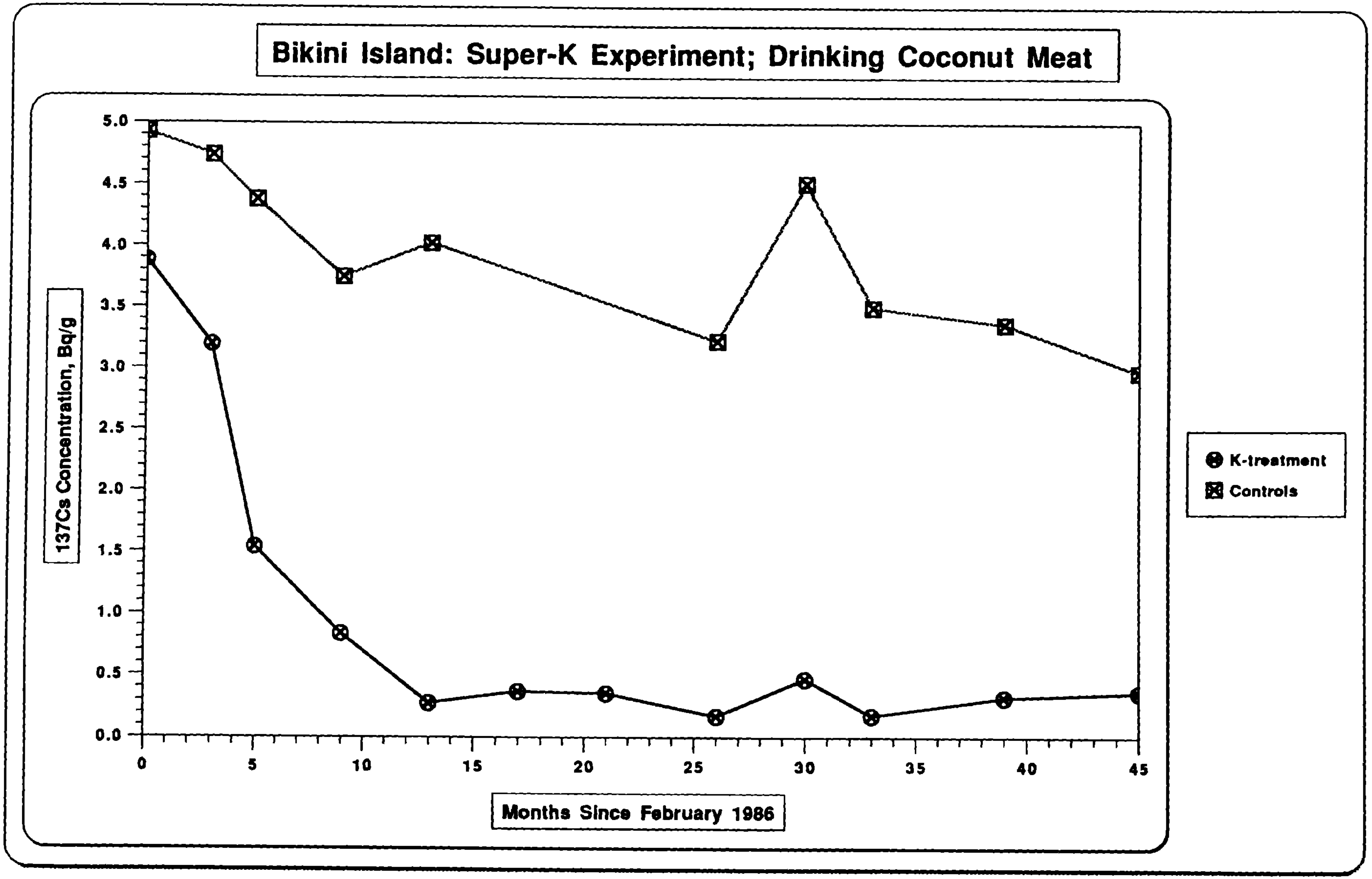

Bikini Island: NPK Field Experiment; Drinking Coconut meat
137Cs Concentration, Bq/g
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
35
40
45
50
55
60
Months Since February, 1985
K 1110
K 2220
K 2220 + NP
K 1110+ NP
K 0 + NP
K 0 (Control)

Figure 3.2.3.3 The effect of a single 5550 kg/ha K application on the uptake of ^{137}Cs in drinking coconuts at Bikini Island.


Bikini Island: Super-K Experiment; Drinking Coconut Meat
137Cs Concentration, Bq/g
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30
35
40
45
Months Since February 1986
K-treatment
Controls